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PHYSIOLOGICAL AND PSYCHOLOGICAL FACTORS IN AIRCRAFT OPERATIONS - AN OVERVIEW

by

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Introduction

The emphasis of aeromedical research has shifted over the past 10 years. The traditional mission of defining human tolerance to environmental factors and protecting the aircrrew against them has been solved to some degree even if further refinement of tolerance limits, their quantitative understanding, and the simultaneous and consecutive interaction of the various stressors deserve further efforts. However, the center of activity has shifted to the performance aspects of the flight environment and to the prediction of aircrrew effectiveness, mission success, and survivability from the complex interaction of environmental, physiological and psychological factors. To an increasing degree basic research studies on the physiological effects of specific environments such as acceleration, heat, vibration and noise were supplemented as realistically as possible by mission simulations, and by attempts to assess and quantitate aircrrew and/or overall weapon systems effectiveness. This trend in laboratory and simulation research clearly enabled a more realistic and quantitative analysis and optimization in the development of new systems.

The new technologies evolving in the form of more sophisticated physiological, behavioral and human operator man-in-the-loop models mark progress in these areas. However, laboratory data and models based on them are always open to criticism, since, in spite of efforts to simulate the real situation, the lack of realism with respect to environment, task, motivation and equipment remains. This criticism is still more justified with respect to extrapolation to combat conditions. The collection and evaluation of operational experiences including combat data collection has probably not progressed as much as laboratory research and simulation. Even if complexity and cost of field studies explain this state of affairs, it is nonetheless important to realize this deficiency. A final contribution to the analysis of pilot/aircrew, as well as systems performance, is provided by accident analysis and interpretation.

The various factors which influence pilot performance and which provide direct or indirect clues to his performance assessment are illustrated in figure 1. The human factors listed in combination with the environmental and operational factors determine his performance potential. The objective workload imposed on him and the human engineering of his tasks determine to what extent this potential is optimally matched to the system under consideration. Realistic performance assessment must therefore occur in a closed loop simulation or through the evaluation of operational mission success. Aeromedical activity and progress of the last 10 years were to a large extent in the areas listed, although most of them are clearly of an interdisciplinary character. Special conferences and symposia of the AGARD Aerospace Medical Panel dealt over the last three years - in addition to the conventional problems of aircrrew selection and health - with problems in these areas as indicated by the titles: "Higher Mental Functioning in Operational Environments"(1), "Vibration and Combined Stresses in Advanced Systems"(2), "The Pathophysiology of High Sustained +Gz Acceleration, Limitation to Air Combat Manoeuvring and the Use of Centrifuges in Performance Training"(3), "Behavioral Aspects of Aircraft Accidents"(4), "Biodynamic Response to Windblast"(5), "Escape Problems and Maneuvers in Combat Aircraft"(6). The following is a brief review of some of the progress and problems organized around the factors listed in figure 1 as major contributors to pilot performance. (The separation of these factors is an idealization justified only by the desire for clear presentations. In reality there is considerable interaction between them. This is particularly true with performance as the output measure. Motivation changes performance under environmental stressors; similarly the engineering of the task and anthropometric factors influence performance for the various environmental and operational factors.) The discussion is neither complete nor exhaustive but rather a summary of some recent progress and an illustration of practical experiences feeding back into the aircraft/cockpit/crew task design.

Pilot Performance/Capability Evaluation and Improvement

a. Human Factors

Anthropometric and kinematic variability of the aircrrew member is still at the heart of many cockpit design problems and is basic to the understanding and alleviation of injuries to personnel involved in ejection incidents. Although conventional anthropometric data are basically available, functional anthropometric and kinematic data to enable optimum positioning and motion capability for all cockpit tasks are missing(7). This is particularly true for new flying tasks and positions, as for example, head-up displays, sights, or the very high performance fighter aircraft with a high acceleration cockpit. Motion capability measured both with and without operational personnel equipment, such as the underarm life preserver and coveralls (and not only for the flight systems tasks but also for the operational combat tasks), must be based on kinematic data as well as static dimensions. The regular use of computers in cockpit design has made the shortcomings in this area obvious. The wide variability in just one static dimension such as the sitting height (figure 2) illustrates the problems one encounters when multi-link motion

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capabilities in new positions must be considered, as for example, with back angles of 65° to 70° (instead of the conventional 13° to 15°). Analysis of ejection statistics gives us a clear indication that pilot stature and position is an important factor in injury probability. USAF accident reporting procedures require selected anthropometric data to be collected on personnel injured upon ejection from aircraft. However, present data acquisition methods when used by untrained, unspecialized personnel are not providing results reliable enough for analysis and corrective action. New low cost photogrammetric systems for this purpose are under development and will hopefully assist future operators in the field with minimum training.

b. Environmental and Operational Factors

Of the environmental factors, vibration stress during low-altitude, high-speed flight missions and performance during high G maneuvers in present and future fighter aircraft have received considerable attention. For both stressors, as well as for other environmental changes such as heat and altitude (hypoxia), models for the human controller in the man-machine system have been developed to predict overall system performance under normal and increasing stress conditions. The potential of this technology to predict performance decrement under stress is very promising; however, the data base for identification of operator parameter changes under stress must be broadened before generalized applications are feasible(8). In addition long-term stress effects such as fatigue or increasing discomfort have not yet been accounted for in these models. However, for the solution of specific problems, as for example, the optimization of the design of the control stick for the vibration environment, the state-variable or "optimal-control" model for the pilot/vehicle system has proven to be very useful(9). In this particular model the operator's error is analyzed in terms of a component correlating with the signal input and two components caused by the vibration effects: the vibration correlated feed-through and the additional remnant or noise in the control output (Fig 3). The latter is split up into perturbation of perception and of control activity. Pilot tracking performance under vibration was investigated as a function of control stick dynamics (stiff versus spring stick). Separation of the errors into their various components exhibited the differences shown in figure 4. Theoretical prediction of the errors by use of the model results in such good agreement with these data (Fig 5), that the model has been proposed for use in control stick design. Although control stick characteristics influence primarily vibration feedthrough, which typically accounts for only a small portion of the increment in tracking error due to vibration, it is nevertheless an important consideration if an inappropriate choice of parameters is to be avoided. A practical application of the model's predictive capability is shown in figure 6: in the vibration environment there is an optimum stick gain at which the output error is a minimum. The minimum is caused by the summation of the vibration feedthrough increasing with stick gain and the tracking related error (remnant) decreasing with increasing stick gain. The model predicts a limited range of optimal stick gain for the vibration environment compared to static conditions.

For evaluation of the operational vibration environments of low-altitude, high-speed flight missions, the exposure criteria for whole-body vibration as defined in the guide of the International Standards Organization(10) and modified for military applications(11) proved to be the best guidance available. These criteria are supported by the limited body of operational data available(2). An example of their application is illustrated in figure 7(12). A shortcoming of this guide was its inapplicability to the vibration range below 1 Hz, where exposure limits are governed by motion sickness, a phenomenon not only highly variable from subject-to-subject and from situation-to-situation but also a phenomenon depending upon other sensory inputs besides whole body motion. Evaluation of newly acquired data and all previously accumulated evidence led to the exposure boundaries of figure 8(13) as the recommended design guidance whenever extension of human transfer functions to this very low frequency range is needed for military use. Exposure up to these levels is expected to result in less than 10% motion sickness in the general population.

With respect to sustained acceleration stress, work is concentrated on exploiting the full performance potential and air combat maneuverability offered by future tactical fighter technology based on high thrust-to-weight ratio engines, advanced lightweight structures and more effective flight control. That pilot G tolerance is improved by a reclined position has been known for a long time (Fig 9). If this physiological protection was to be used in practical high acceleration cockpit designs, pilot-system flight effectiveness as well as combat effectiveness at higher G loads had to be proven by extensive studies and simulations. Various designs for articulating seats evolved which would allow the pilot to assume the reclined position for maneuvering G-protection but return to the upright position for the remainder of the mission. Two such design concepts are illustrated in figure 10; the seat rotation does not interfere with the ejection capability in the normal upright position. Pilot effectiveness is increased as illustrated in figure 11. The design problems with respect to anthropometry as well as performance capability for such a two-position seat are enormous; full combat vision, control of flight and armament functions must be retained for all seat positions. Ejection capability as well as normal flight efficiency and comfort must not be compromised. Cockpit design studies demonstrated that such an articulating seat can be integrated into an advanced fighter cockpit to provide full system effectiveness(14). The crew integration issues addressed are summarized in figure 12. A quantitative estimate of the advantage of incorporating a high acceleration cockpit into current fighters (7.5 G structure) and into a high acceleration fighter (10.5 G structure) was obtained from complete man-in-the-loop real-time combat encounters using experienced fighter pilots and a fixed base simulator(16). The trend observed in these studies of duels between the HAC-equipped

fighters against conventional fighters is illustrated in figure 13. Other manned simulation studies to measure combat effectiveness for various starting conditions for the fight all support this trend and emphasize that design for physiological protection and combat performance effectiveness can go hand in hand and can bring about the hoped for results.

Another environmental and/or human factor to be mentioned which has been investigated extensively with respect to its effect on pilot performance and air operations is the circadian biorhythm, modulating the activity of most body functions over the daily 24-hr period. In this area too, emphasis shifted from physiological studies to performance evaluations. The vast amount of evidence accumulated(17) shows that human performance as a function of the time of day shows a similar fluctuation as the physiological functions (Fig 14). Performance basically follows the rhythm of body temperature. The range of oscillation of the various performance measures varies between 12% and 25% of the 24-hour mean whereas the physiological fluctuations are much higher. The general dependency illustrated in figure 14 can be modified within limits by disposition, training, motivation, personality, change of the sleep-rest cycle and changes in the environment. The latter two are typical factors in air operations which lead to desynchronization of the performance rhythms and a temporary lowering of the 24-hour mean performance. The time constants for desynchronization and subsequent resynchronization have been extensively studied in laboratory, as well as operational transatlantic experiments with transmeridian time shifts, over 6 and 8 hours. The results have led to several recommendations with respect to the scheduling of night duty in general and the scheduling of transmeridian flights and world-wide operations in general. Disregard of circadian desynchronization has been implicated as a potential factor in major civil aviation accidents. Application of the rules learned in this field appears clearly indicated.

#### c. Workload

Without going into the complexity of the detailed definitions of the workload concept and the various approaches to workload measurements, a few comments on progress and direction in this area may be in order. Workload is the input load presented to the operator; its measurement is only meaningful in terms of operator effort, operator capacity and the resulting work output. Workload can be characterized by psychological, physiological and operational criteria, each of these being used by itself successfully for specific applications; but in reality it is clear that only the sum of these three factors can give the final answer. In a model such as the one indicated in figure 1 workload is often simplified to the ratio of required crew/equipment performance time to the time available for execution. Workload capacity has been frequently measured by introducing one or more auxiliary tasks and evaluating performance on the secondary tasks and influences of the additional task's stress on the primary task performance. Strategy of time sharing and priority assignment is important for the final workload assessment. Recently, progress in the identification of human controller model parameters has led to attempts to measure differential changes in the model parameters under increasing workload or environmental or psychological stress, and to characterize workload by these parameter changes. This control theory approach is very appealing since the model parameters are hypothesized to correlate with specific physiological control parameters and higher mental functions(18)(19). It might primarily be valid for the traditional pilot functions requiring perceptual and manual control skills. However, the new types of systems envisioned for future aircraft, making increasing use of on-board computers to select and control a large number of aircrew tasks, change the type of load and performance requirements imposed on the pilot. Capability to memorize long sequences of operations and to select between programs and displays are envisioned to become the primary piloting functions and replace to a large extent manual control task requirements. As a consequence, assessment methodologies are being developed which test, in addition to manual tracking, cognitive skills, memory, information processing and sequencing(20).

Pilot workload is influenced by the human engineering of the man-machine interface. Modeling of this interface and assessment of the simulated or actual pilot load through physiological or psychological indicators are only the initial steps in a human factors engineering program. It is essential that the researchers, as well as the designers, receive continuous feedback from operators' experience. This feedback, the requirement for which is so obvious, is difficult to maintain in today's environment of specialization.

#### d. Mission Success/Accident Evaluation

Physiological and performance studies in the operational environment are difficult to perform, relatively expensive, and produce data which are usually aircraft and mission specific and do not allow too much generalization. They are frequently not too well received by the operators and are therefore seldom done with satisfying thoroughness - unless there are obvious operational problems. Such problems might be accidents or incidents of impairment of mission effectiveness. Without such problems few operational studies are done, and the above-mentioned feedback is minimal. The result of this state of affairs is that intolerable problems are resolved but few tolerable situations are improved and still fewer good situations are made better. In most mission studies emphasis is on stress and fatigue, the factors hard to simulate realistically. A variety of psychological and physiological parameters are being measured and compared to pretest baseline studies and to values accumulated from similar investigations. Scientifically, these studies are often not very exciting, but the sum of the test results allows a valid judgment of crew effectiveness and/or vulnerability.

Two recent examples of such tests will be mentioned. The first one was a biomedical evaluation of the physiological costs of extended airborne command and control operations(21). In Exercise Night Star the ability of the National Emergency Airborne Command Post was tested to maintain a continuous airborne alert for an extended period of several days. Three mission teams of 17 members each were followed through the 4 missions of 8-1/2 to 12 hours duration using both subjective and objective evaluation methods. Physiological costs were judged from urine analysis, oral temperature, fatigue forms and sleep histories. Psychological results were obtained from subjective rating of mood, alertness and coordination, and from critical incident surveys, debriefings and observations. Physiological evaluation as judged by the metabolic indices indicated mild to moderate stress of a degree known from previous studies to be compatible with sustained crew performance and not resulting in performance decrement. The work schedule could have been maintained for additional missions if necessary. Psychologically the exercise produced only mild fatigue, as demonstrated in figure 15, although the fatigue was always greater than on the control days. With the exception of the first 12 hour mission, the fatigue level seldom fell below a score of 9. Experience has shown that complete recovery from this fatigue level occurs after an 8-hour sleep. The low score of 6.7 in Team III after the first mission - a score indicating moderate persistent psychological cost - was probably the result of the 12-hour alert duty preceding the first 12-hour flight at the beginning of the exercise. Overall there was only a small indication of cumulative fatigue in Team III evidenced by the low score early in the fourth mission. In summary, the test clearly demonstrated that airborne alerts without decrement in performance would be biomedically feasible for periods longer than Exercise Night Star.

The second example of operational study of biomedical cost involved low-level reconnaissance flying in the RF-4C aircraft(22). The RF-4C pilots and weapon systems operators (total of 47) were evaluated by similar methods as in the previous study. Urine analysis, heart rate, oral and skin temperature, and sleep score were the physiological parameters evaluated. The most significant findings pointed toward moderate heat stress and acute dehydration as a result of missions during the hot summer months. Cockpit temperature (Fig 16) in summer during the high-speed, low-level flight mission was often over 40°C, and sometimes even over 50°C. It would have been hard to predict from laboratory tests if and how severe a performance decrement might result from this amount of heat stress. The operational results (Fig 17) clearly indicated that the photo target acquisition scores deteriorated during the summer months. Nearly twice as many targets were missed during the summer months than during winter! Completely successful missions were significantly more likely during winter time. The degree of dehydration found has been observed in laboratory experiments to result in a 15 to 18% decrease in G tolerance, an additional stress effect which could have reduced the margin of safety under specific circumstances. Needless to say that the primary result of this particular study was the recommendation for improvement of the cockpit air conditioning system of the RF-4C.

The final example to be mentioned of aeromedical investigations based on operational experience concerns the efforts to reduce the probability of injury to the aircrewman during escape maneuvers. Unfortunately, in spite of our tremendous technological progress in this area, the probability of injury during escape has not markedly changed over the course of the last 20 years. The reason for this is probably the higher escape speed and the increased complexity of the systems. Over the past 10 years aeromedical work focused on the primary injury mode: spinal injury due to the ejection forces. Accident statistics, detailed analysis of accident reports and laboratory research on spinal dynamics and strength led to a biodynamic model of the crewman under the longitudinal acceleration load. This model allows prediction of the probability of spinal injury for arbitrary force-time functions and has proven to be a valuable design tool(23). Work on refinement of this model in conjunction with the evaluation of newly accumulating spinal injury statistics is going on. In the last few years emphasis shifted to a secondary injury mode, the injuries caused by the aerodynamic forces after separation of the seat from the aircraft. Analysis of the statistics and a research effort going individually over the accident records revealed that the assumption that ejection below 600 knots would result in only minor injury was incorrect. Restraint of the crewman proved to be inadequate to prevent serious injuries due to limb flailing. The probability of flail injury as a function of escape speed is shown in figure 18(24). The overall incidence of major flail injury in non-combat ejections amounts to approximately 4%, but rises to 22% for ejections above 300 KIAS(25). Since combat ejections appear to occur on the average at almost twice the escape speed of non-combat ejections, major flail injury in combat ejections was found to occur in 9% of the cases. Of 44 flail injury cases 16 were found to involve the head and neck, 34 the upper limb and 24 the lower limb. The follow-on program is now directed toward defining the forces acting on the body segments and understanding the mechanisms leading to limb displacement and tissue failure. Wind tunnel tests with live subjects in operational clothing seated in various types of ejection seats are aimed at measuring aerodynamic stability and limb dislodgement forces with the various seats (26)(27). As an example from the large body of data collected, figure 19 illustrates the differences in knee separation forces experienced with various ejection control handle positions. Similarly, data on forces acting on the helmet for different speeds and seat angles have been collected. Helmet retention and head-neck injury from windblast or on ground landing - with helmet retained or with helmet lost - are special phases of this effort. It is hoped that this overall program will define the forces acting on the man and provide the biological exposure limits which are required for the development of protective countermeasures aimed at either reducing the forces or increasing restraint capability.

The prospect derived from the operational reality that under combat conditions roughly half of all open seat ejectionees face flail injury or fatality(24) emphasizes the

need for better data and new approaches in this area.

#### Conclusions

This overview of current aeromedical efforts, achievements and trends and their relation to operational experiences is by necessity sketchy and incomplete. In addition, it is probably biased by the author's own experiences, and interests. In spite of these shortcomings it is hoped that it has reviewed some of the major research thrusts which are based on observations, measurements or statistics from the operational environment. The results lead in most cases to reorientation of laboratory research interests and to improvements of methods and technologies, which in turn, we hope, contribute to improved systems concepts, designs and operations. Main progress was probably characterized by advances in two areas:

a. The technologies of modeling human biodynamic response to force environments, of modeling human performance under environmental stressors, and of modeling the man-machine interface have advanced to the point where the models can provide, in many cases, quantitative design guidance in place of qualitative interpretation, to increase safety and crew performance capability.

b. Efforts to define, measure and predict the airmen's capability are generally more directed at evaluating overall weapon systems effectiveness. Physiological and psychological factors are both studied in more realistic closed-loop laboratory mission simulations as well as in operational field studies, with the primary goal to characterize man's overall performance capability and limitations as the operator of specific systems on specific missions.

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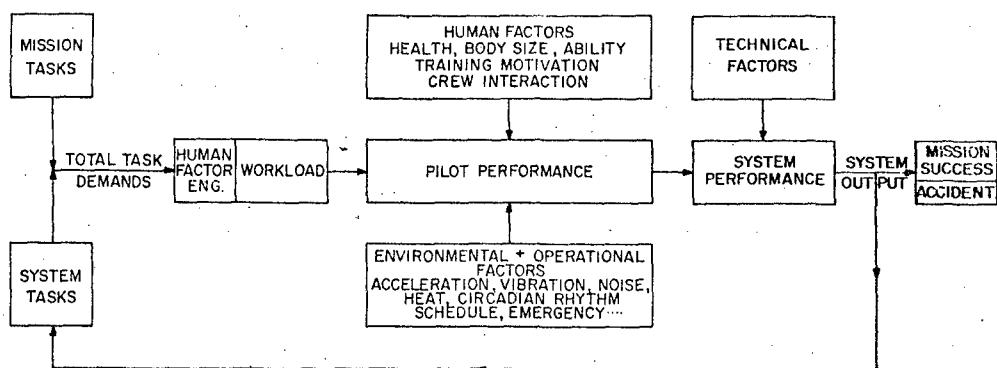


Fig. 1. Factors determining pilot performance and used in its evaluation.

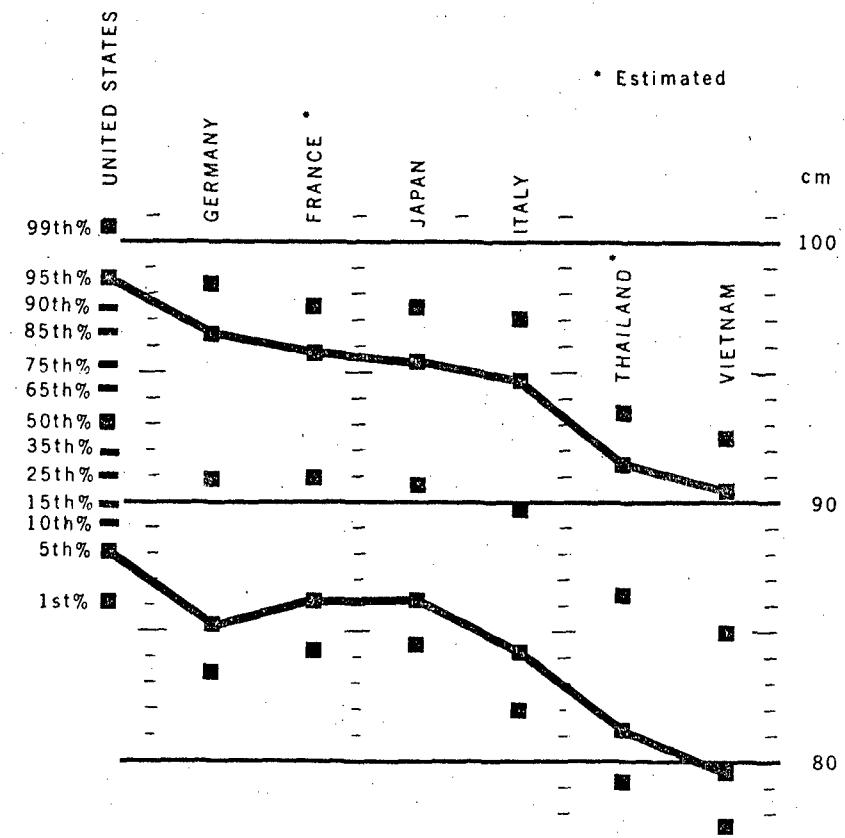


Fig. 2. Comparative percentile values for sitting height: selected military populations (from ref. 7).

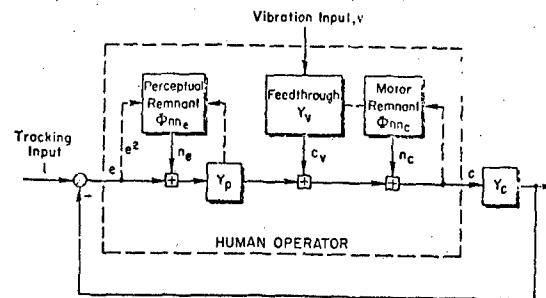


Fig. 3. Human operator model for describing vibration effects on manual control performance (from ref. 9).

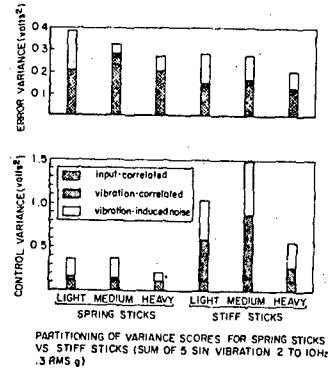


Fig. 4. Pilot tracking performance under vibration (side stick versus center stick): components of error (from ref. 9).

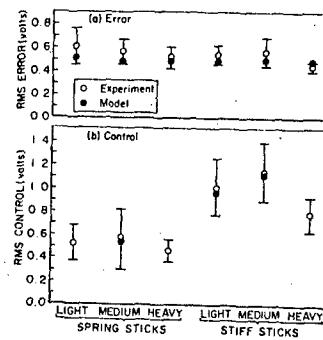


Fig. 5. Comparison of theoretical prediction of errors by use of human operator model with measured data (from ref. 9).

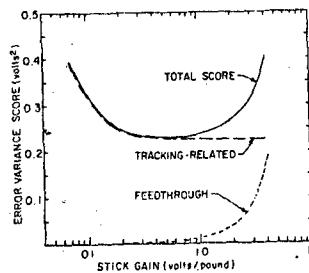


Fig. 6. Output error versus stick gain for tracking performance under vibration (0.3 g<sub>z</sub> rms) (from ref. 9).

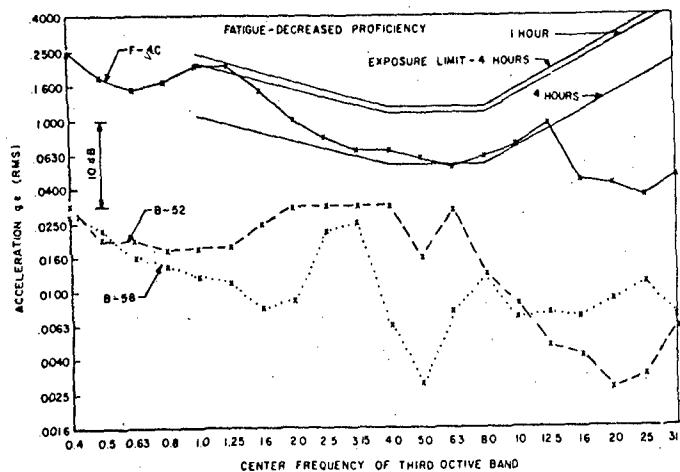


Fig. 7. Comparison of the maximum Z-axis third octave band acceleration levels measured at the pilot's seat in low-altitude, high-speed flight missions over mountainous terrain with the 4-hr exposure limit and the 1 and 4-hr fatigue-decreased proficiency boundary (from ref. 12).

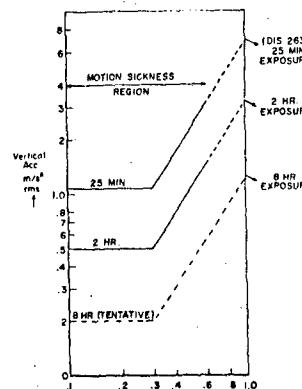


Fig. 8. Proposed "severe discomfort boundaries" for various exposure times for the 0.1 to 1 Hz frequency range (from ref. 13).

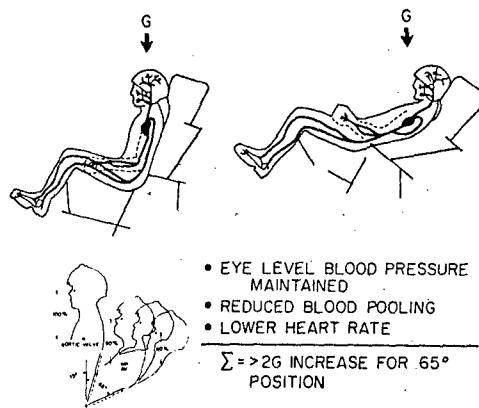


Fig. 9. Improvement of pilot's G-tolerance through reclined position (from ref. 14). The lower figure illustrates the use of an anthropometrically and kinematically correct drawing board manikin (5 percentile) in determining optimum head position to improve G-tolerance. The difference between the three head positions for constant back angle amounts to 30% of the eye level-heart hydrostatic column (from ref. 15).

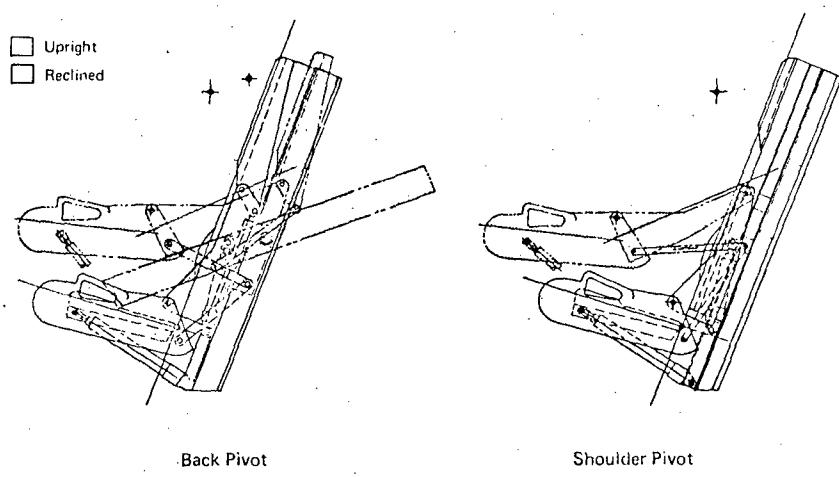


Fig. 10. Comparison of two seat design concepts tested for the high acceleration cockpit (from ref. 14).

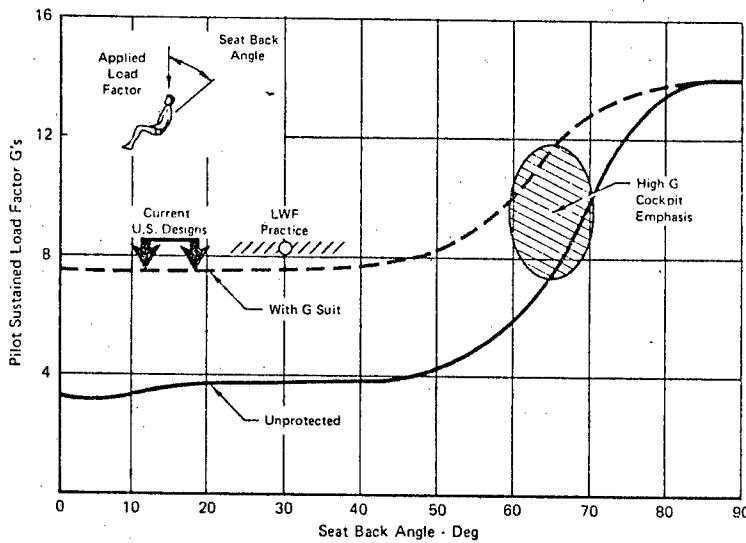


Fig. 11. Pilot sustained G-tolerance as a function of seat back angle (from ref. 14).

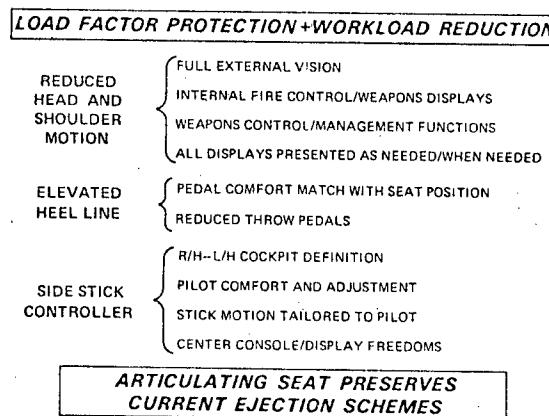


Fig. 12. Pilot/vehicle interface problems addressed in the high acceleration cockpit design studies (from ref. 16).

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DIGITAL PILOTS - 36 ENGAGEMENTS

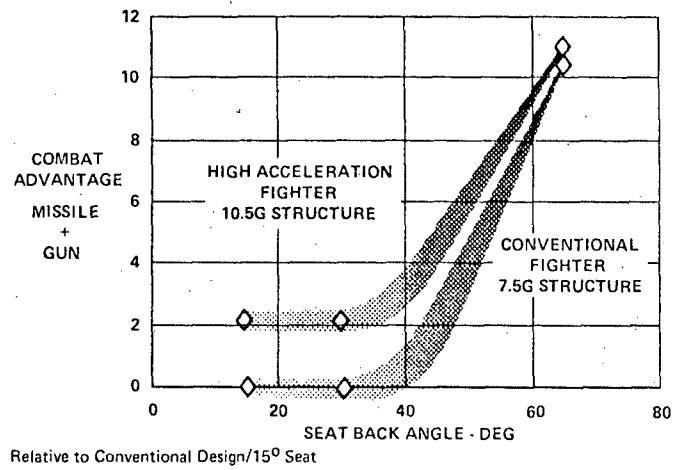


Fig. 13. Air combat maneuvering modeling results. (The 36 engagements were for both fair fight and biased initial conditions.) The combat advantage over a conventional fighter without reclining seat (high acceleration cockpit) is shown (from ref. 16).

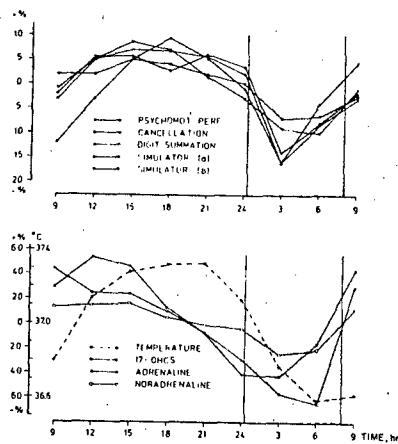


Fig. 14. Circadian rhythms of behavioral and physiological functioning. (in percent of 24-hr mean; body temperature in °C.)(from ref. 17).

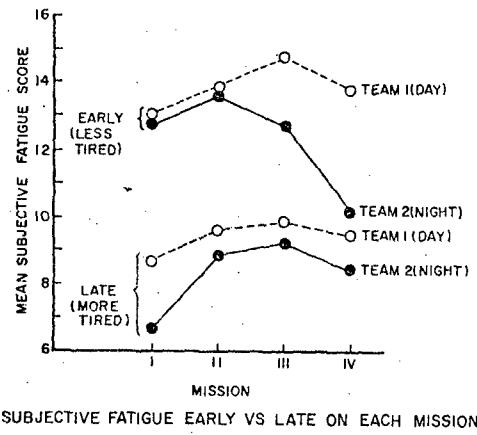


Fig. 15. Mean subjective fatigue scores early versus late on each of the four missions of Exercise Night Star. (Lower scores indicate increasing fatigue.) From fatigue Level 9 complete recovery occurs after an 8-hour sleep period (from ref. 21).

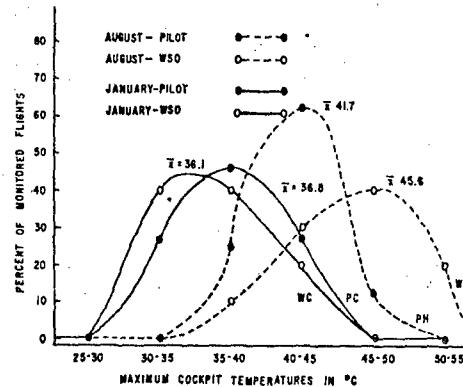


Fig. 16. Comparison of summer versus winter cockpit temperatures at the pilot's and weapon systems operator's position in the RF-4C aircraft during low-level flight missions (from ref. 22).

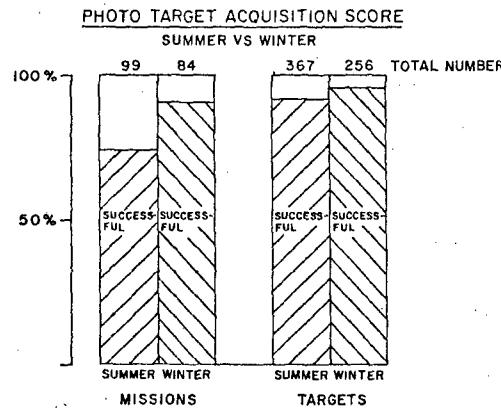


Fig. 17. Comparison of photo target acquisition scores of RF-4C missions summer versus winter (from ref. 22).

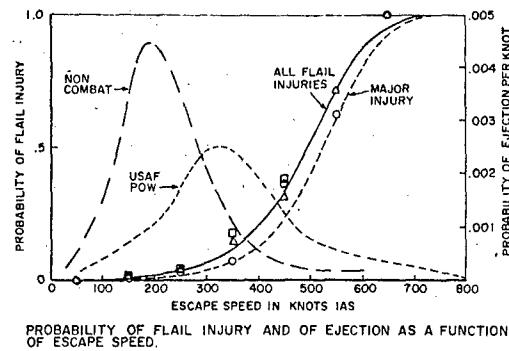


Fig. 18. Probability of non-combat flailing injuries as a function of escape speed (from ref. 24).

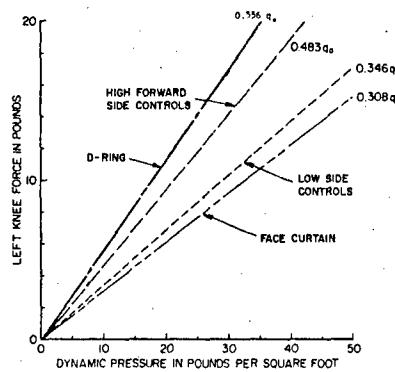


Fig. 19. Effects of ejection control handle position on knee separation force.  
(Data measured in wind tunnel on human volunteers in USAF flight clothing.)  
(from ref. 26).